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Supernovae and gamma-ray bursts connection

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The status of the Supernova/Gamma-Ray Burst connection is reviewed. There is clear evidence that long duration Gamma-ray Bursts are associated with broad-line SNe-Ib/c, although some new studies show that GRBs could be produced in tight binary systems which consist of a massive Wolf–Rayet star and a neutron star companion. Present estimates produce a ratio GRB/SNe-Ibc in the range ∼0.4%–3%.

Keywords: Supernovae; gamma-ray bursts; black holes

1 Introduction

This talk is dedicated to the memory of Professor Evgenii Pavlovich Mazets (1929–2013) of the Ioffe Physical Technical Institute, St Petersburg, in recognition of his important contribution to the physics of gamma-ray bursts and to the Konus Wind experiment.

The investigation and review of Gamma-ray Bursts (GRBs) which was completed over the last 15 years using ground-based telescopes has confirmed that long duration GRBs are related to the death of massive stars. This outcome is based on the following evidence: (i) the discovery of 6 cases of associations within $z \lesssim 0.2$ [34, 42, 89, 58, 9, 75, 7, 26] between “broad lined” SNe-Ic (sometimes termed as Hypernovae, hereafter HNe) and GRBs; (ii) spectroscopic observations of the rebrightenings observed during the tailing off of the afterglows have indicated the presence of SN features [18, 20, 23, 84, 45]; (iii) the host galaxies of long GRBs are star forming galaxies [25, 30]; (iv) GRBs and SNe-Ic SNe occur in similar environments [48, 79]; (v) observations of borderline events such as SN 2008D associated with the X ray transient 080109 indicate a continuum of properties in GRB-SNe: at the upper region there are “ultra-luminous GRBs” such as GRB130702A/SN2013dx ($E_{\rm iso} \sim 10^{54}$ erg), followed by “luminous GRBs” such as GRB030323/SN2003dh ($E_{\rm iso} \sim 10^{51}$ erg),

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and then "underluminous" events, like XRF 060218/SN 2006aj $\sim 10^{49}$ erg and finally "failed GRBs"/"shock break-out" events X080109/SN 2008D ($\sim 10^{46}$ erg).

Based on this evidence, there are several theoretical scenarios which have been described and refined over the last 15 years. These scenarios can be broadly split into two groups: a) long duration GRBs are product of the collapse of a single Wolf–Rayet (H/He stripped out) star (e.g. [98, 28]); b) long duration GRBs are the product of binary driven hypernova events, which are binary systems composed of a W-R star and a neutron star [81, 44, 80, 29]. In this case the ejecta produced by the explosion of the W–R progenitor as SNe-Ib/c trigger a hypercritical accretion process onto the NS companion which collapses to a black hole and then emitting a GRB.

2 GRB–SN associations at $z < 0.2$

2.1 GRB 980425/SN 1998bw

GRB 980425 was discovered in ESO 184-G82 ($z = 0.085$) and it was underpowered by 4 orders of magnitude with reference to the "standard" cosmological reservoir of 10^{51} erg [27, 71]. The associated SN was classified as part of the Ibc class [74], though characterized by unusually high expansion velocities of about 30,000 km/s, which is larger by about a factor of 3 than that observed in "no-GRB SNe". The bright magnitude at maximum, $M_V \sim -19$, places SN 1998bw into the luminous tail of the distribution of SNe-Ibc magnitudes [78]. The radio emitting region associated with this GRB-SN was expanding at mildly relativistic velocities ($\Gamma \sim 2$ [51]). The theoretical modeling of the light curve and spectra indicates that SN 1998bw is the product of the explosion of an H-envelope stripped star, of about 40 $M_\odot$ on the main sequence (e.g. [96, 70]). Maeda et al. (2006) have modeled the bolometric lightcurve of SN 1998bw with a smaller amount of ^{56}Ni (~ 0.4 $M_\odot$) by assuming that the SN explosion was highly asymmetric (see also [43]).

2.2 GRB 030329/SN 2003dh

SN 2003dh was found to be associated with GRB 030329 at a redshift $z = 0.1685$ [37]. SN features were rapidly detected in the spectra of the afterglow by several groups [89, 42, 47, 62]. Both the gamma-ray energy budget and afterglow properties of this GRB were similar to those observed in the so called "cosmological" GRBs, and therefore, the link between GRBs and SNe was finally established to be more general. The modeling of the early spectra of SN 2003dh shows that the progenitor was a massive envelope-stripped star of $\sim$35–40 $M_\odot$ on the main sequence [63].

2.3 GRB 031203/SN 2003lw

GRB 031203 was observed at $z = 0.1055$ [77, 60]. The burst energy, 10^{49} erg [6], was fainter by two orders of magnitude than the "standard" $\sim 10^{51}$ erg of "cosmological" GRBs. A few days after the GRB, a rebrightening was apparent in all optical bands [14, 32, 91]. Spectra of the rebrightening obtained 2 and 3 weeks after the GRB (GRB rest-frame), were similar to those of SN 1998bw obtained at comparable epochs [58].

The light curve of SN 2003lw is characterized by a slower temporal evolution than SN 1998bw (by ∼10%) and it may be brighter than SN 1998bw up to 0.3 mag. However we note that the significant uncertainty (about 0.5 mag) is mostly due to the correction for reddening to this object. An analysis of its photometric and spectroscopic evolution [64] suggests that this Hypernova had a main sequence mass of $\sim 40\ M_\odot$.

2.4 GRB 060218/SN 2006aj

GRB 060218 was identified by Swift at $z = 0.033$. This burst was unusually long, with $T_{90} \sim 2100s$. Timely observations of the UVOT telescope revealed an emission peaking first at UV wavelengths and later in the optical [9, 17]. Almost simultaneously low resolution spectra obtained at VLT [75] indicated the presence of a rising SN (2006aj) with broad emission lines similar to those observed in other GRB-SNe. The most striking feature of this event is the presence of a thermal component observed in the XRT data, up to 10 ks, and in the UVOT data, up to about 100 ks. This black body component shows a decreasing temperature as well as an increasing luminosity, which implies an increase in the apparent emission radius up to $\sim 3\times 10^{14}$ cm in about 100 ks, corresponding to an expansion velocity of the order of 30,000 km/s, which is typical of SNe associated with GRBs. After assuming linear expansion one can deduce the initial radius of the progenitor star to be of the order of 5×10^{11} cm which is comparable to the size of a Wolf–Rayet star. The (UV) black-body component has been explained in terms of a shock break-out wave, produced after the collapse of the core, emerging from the region within which the stellar wind of the massive progenitor is optically thick (about 10^{13} cm, see [10, 72]). This explanation has been disputed by several authors (e.g. [36]).

2.5 GRB 100316D/SN 2010bh

GRB 100316D was discovered by Swift at $z = 0.059$. The associated SN was easily identified due to the close proximity of this event and it was confirmed as a SN type Ic. An intensive follow-up of SN 2010bh was completed at the ESO Very Large Telescope equipped with X-shooter and FORS2 instruments [7]. SN 2010bh was characterized by a rapid rise to maximum brightness (8.0 rest-frame days) and a relatively faint absolute peak luminosity ($L_{\rm bol} \sim 3 \times 10^{42}$ erg s^{-1}) than that previously observed in SNe associated with GRBs. Spectroscopic observations have allowed us to measure expansion velocities up to 50,000 km s^{-1}, which is much higher than that observed in SNe 1998bw (GRB 980425) and 2006aj (GRB 060218). The shape of the lightcurve and large photospheric expansion velocities of SN 2010bh indicates that this was a highly energetic explosion with a small ejected mass ($E_K \sim 10^{52}$ erg and $M_{\rm ej} \lesssim 3M_\odot$) characterized by a small value of $E_{\rm iso} \sim 10^{49-50}$ [61]. The observed properties of SN 2010bh confirm and extend the heterogeneous phenomenology of GRB-SNe.

2.6 GRB 130702A/SN 2013dx

GRB 130702A occurred in a dwarf galaxy satellite of a massive galaxy at $z = 0.145$ [49]. This GRB, characterized by an $E_{\rm iso} \sim 10^{50/51}$, was associated with the type Ic

SN 2013dx [26]. The bolometric lightcurve of SN 2013dx is similar to that of 2003dh (associated with GRB 030329), although it is 10% faster and 25% dimmer. Interestingly enough, multi-epoch optical spectroscopy shows that the SN 2013dx behavior is best matched by SN 2010ah, which is an energetic type Ic SN, not associated with any GRB. The photospheric velocity of the ejected material decreases from $\sim 30\times10^3$ km s^{-1} to $\sim 3.5\times10^3$ km s^{-1} in about one month.

3 SN/GRB associations at $z > 0.2$

3.1 GRB 021211/SN 2002lt

GRB 021211 was discovered by the HETE–2 satellite at $z = 1.006$ ([95]. Late-time photometric follow-up, carried out with the ESO VLT–UT4, together with HST observations, show a rebrightening, starting ∼15 days after the burst and reaching the maximum ($R \sim 24.5$) during the first week of January. A spectrum of the afterglow obtained with FORS 2, during the rebrightening [18] showed broad low-amplitude undulations blueward and redward of a broad absorption, the minimum of which was measured at ∼3770 Å (in the rest frame of the GRB), whereas its blue wing extends up to ∼3650 Å. The comparison with the spectra of other SNe suggests that SN1994I is the spectrum which provides the best match to that of GRB 021211. However SN 1994I is a "typical" type-Ic event rather than a Hypernova. One possible interpretation is that the spectrum of SN 2002lt has been obtained about 15 days (rest-frame) past maximum and even if its pre-maximum spectra could show significantly broader lines, this difference would have disappeared after maximum, because of the small amount of mass dispersed by the high-velocity ejecta. Therefore for this reason the possibility to make a clear distinction between "standard" SNe-Ic and "GRB-SNe" vanishes with time. A piece of evidence in this direction comes from the recent finding of [11]. These authors present a spectrum of SN 2013ez/GRB 130215A, obtained some days past maximum, which is characterized by relatively low expansion velocities ($\lesssim$10,000 km/s) typical of "standard" SNe-Ic rather than HNe. The large spread observed in the expansion velocities of GRB-SNe may indicate the existence of a large extend in the mass of ejecta.

3.2 GRB 050525A/SN 2005nc

The long-duration GRB 050525A was discovered by the *Swift* satellite at $z = 0.606$. Photometric data display a plateau of the lightcurve at $R \sim 24$, beginning about 5d after the burst (observer rest frame) and continuing for about 20 d [20]. The contribution of the host galaxy during this phase is ∼40%, as estimated from our late-epoch images (which show that the host magnitude is fainter than $R \sim 25$) while the afterglow contribution is negligible (<3% at 20d after the GRB). A low resolution spectrum, obtained at the ESO-VLT 22d after the burst (GRB rest-frame) shows some similarities with the spectrum of SN 1998bw obtained 5d past maximum and dimmed by ≈0.9 mag [20].

3.3 GRB 081007/SN 2008hw

ESO-VLT spectroscopic observations of the optical counterpart of GRB 081009 [23, 2, 16, 88, 45] at $z = 0.53$ [4] obtained at two epochs past maximum indicate the presence of broad bumps at about 4600, 5400, and 6400 Å, which are very similar to those observed in the spectrum of SN 1998bw about one week past maximum. The photometric follow-up carried out with GROND [38] at the MPI/ESO 2.2-m telescope (La Silla, Chile), starting from about 1000 s after the Swift/BAT trigger, reveals the presence of a plateau at about 7 days after the gamma-ray burst (rest frame), which supports the presence of a supernova superimposed on the afterglow.

To date 35 GRB-SN associations have been detected. For an updated census see Table 1 of [50].

4 The link between Supernovae and GRBs

In 2008 January 9.57 UT the X-Ray Telescope (XRT) on board Swift detected GRB 08010 in the galaxy NGC2770 [5]. Prompt optical follow-up exposed the presence of an associated supernova, SN 2008D, [24] and early spectra [93] showed broad absorption lines superimposed on a blue continuum. The lack of hydrogen or helium lines indicated a classification of type Ic. The spectra are similar to those of GRB060218/SN 2006aj although much more reddened, $E(B-V)_{\rm tot} = 0.65$ mag [65]. An unusual feature is the spectral metamorphosis: unlike other GRB-SNe the broad absorptions did not persist and shortly after they disappeared, while He I lines are developed [67].

Ref. [65, 90] have reproduced the spectral evolution and the lightcurve of SN 2008D through the explosion of a ∼25–30 $M_\odot$ main sequence star and $KE \sim 6\times10^{51}$ erg, only 8% of which related to material moving at $v > 0.1c$. Its quick disappearance implies that the mass moving at high velocities was small, possibly of the order of 0.03 $M_\odot$. The kinetic energy of this event, computed assuming spherical symmetry, although smaller than the "canonical" $KE \sim 10^{52}$ erg associated with HNe is definitely larger than that measured in "non-GRBs" SNe.

The X-ray spectrum of SN 2008D can be fitted with either a simple power-law indicating a non-thermal emission mechanism or a combination of a hot black body ($T = 3.8 \times 10^6$ K) and a power law. In the latter case, the black-body contribution is a small fraction of the total X-ray luminosity (about 14%) and the angular size (about 6°) of the emitting area (radius $R_{\rm ph} \sim 10^{10}$ cm) is typical of GRB jets. This fact leads naturally to a scenario [65], which is alternative to the shock break-out model proposed by [87] (see also [13]). GRB 080109 might be the breakout of a failed relativistic jet powered by a central engine (see also [53, 99]). The jet failed because its energy was initially low or because it was damped by the He layer, which is absent in GRB-HNe, or for both.

5 Hypernova and GRB rates

After combining the local density of B luminosity (e.g. [55]) with the rate of SNe measured in late-type galaxies [12, 54], we find a rate of ∼2 $\times10^4$ SNe-Ibc Gpc^{-3}

yr^{-1}. This value has to be compared with the rate of "cosmological" GRBs of ∼1 GRB Gpc^{-3} yr^{-1} [82, 41], rescaled for the jet beaming factor, f_b^{-1}: ∼ 75 [39] up to ∼500 [27], corresponding to beaming angles ∼10°–4° respectively. These figures provide a ratio GRB/SNe-Ibc in the range: ∼0.4%–3% (see [22, 40]). Radio surveys result in similar constraints: GRB/SNe-Ibc <10% [85].

Several authors (e.g. [19, 75, 86, 15, 1]) have noted that the volume sampled by sub-energetic GRBs is smaller, by a factor $\sim 10^6$, than that probed by cosmological GRBs, therefore the number of sub–energetic GRBs may well be higher, even by orders of magnitude, than that of "cosmological" GRBs. However, we have found [40] that sub-energetic GRBs are, on average, much less collimated than "cosmological" GRBs, likely $\mathrm{f}_b^{-1} \lesssim 10$, therefore the discrepancy between the intrinsic frequency of occurrence of the two types of GRBs could be significantly smaller, possibly of the order of a factor of $\lesssim$10.

6 Long duration GRBs without (bright) Supernova

Observations of the long duration GRB 060614 [21, 31, 33] challenge the simple idea that all long duration GRBs are products of SN explosions. VLT and HST observations of this GRB have indicated that the magnitude of any "potential" SN associated with it was at least 200 times fainter (in R band) than the other GRB-SNe. This result may suggest scenarios in which the GRB is produced without an accompanying SN such as for example the transition neutron star to quark star [3] or a merging event ([35, 8, 46]. We have proposed [21] as a possible explanation that most ^{56}Ni produced during the late stages of the stellar evolution of the progenitor star is not ejected with the envelopes, as commonly observed in the broad-lined SNe-Ibc associated with GRBs, but it falls back into the newborn black-hole. If this is the case, the only *Ni* that can escape from the the exploding progenitor is that which is confined in the jets (see [92] for the theoretical details), that is, less than $\sim 10^{-4}$ $M_\odot$. Such a small amount of ^{56}Ni would explain the extreme faintness (M_B fainter than −13) of a possible SN associated with GRB 060614. This scenario received some indirect support through the detection of a few unusually faint core-collapse SNe [73, 94].

Conclusions

Observations of GRBs over the last ∼15 years have led to significant advances in our understanding of the GRB-SN phenomenon, and the following are a summary of important results:

i) Long duration GRBs are linked to death of massive stars. This fact is well documented by: a) the direct observations of six SNe associated with GRBs; b) some dozens of rebrightenings discovered during the late stages of the afterglows, are well reproduced by adding SN components to the afterglow lightcurves. In some cases SN features have been detected in the spectra of the "bumps"; c) most host galaxies of long GRBs exhibit an intense star forming activity; d) GRBs and SNe-Ic seem to be located in similar environments.

ii) Observations of GRB 060218 coupled with simple theoretical reasoning indicate that the progenitor star of the associated SN (2006aj) had a radius of about $\sim 5 \times 10^{11}$ cm. This is similar to the size of a Wolf–Rayet star and fully consistent with the fact that all GRB-SNe, so far observed, belong to Ic types, i.e., they are derived from the collapse of H/He stripped-off massive stars. There is growing evidence, based on both observational [83] and theoretical grounds [81, 44, 80, 29] that these GRB-SN events occur in a binary system formed by a neutron star and a Wolf–Rayet companion.

iii) Only 0.4%−3% of SNe-Ibc (corresponding to $\ll 1\%$ of all core-collapse SNe) are capable of producing GRBs. Therefore there are some special circumstances which are required for a massive star to become a GRB progenitor. Several studies indicate that asymmetry in the SN explosions [68, 57], rotation [97, 100], metallicity [30, 69], binarity [76, 66] may all play an important role (see [10]).

iv) The discovery of GRB 060218 at $z = 0.03$ has raised the question of whether or not a population of "local" and "low-luminosity" GRBs ($\lesssim 10^{49}$ erg s^{-1}) with different properties from the energetically "high-luminosity" cosmological GRBs does exist ($\gtrsim 10^{51}$ erg s^{-1}). Since the volume that they sample is $\sim 10^6$ times smaller than that probed by cosmological GRBs, the rate of these events could be larger, perhaps they are the most common GRBs in the Universe.

v) GRB 060614 questions the "well-established" idea that all long duration GRBs are produced in bright Supernova explosions. Indeed any SN potentially associated with this GRB was at least 200 times fainter (in R band) than the other GRB-SNe. This fact may suggest that GRB 060614 was either the prototype of a new class of long-duration GRB which are produced in a new kind of massive star death ("fall-back" or "dark" Supernovae), different from those producing bright SNe-Ibc or it was the product of coalescence of compact stellar remnants (e.g. two neutron stars).

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